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DESIGN OF AN AUTONOMOUS LUNAR
CONSTRUCTION UTILITY VEHICLE

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In order to prepare a site for a manned lunar base, an autonomously operated construction vehicle is necessary. In this report, a Lunar Construction Utility Vehicle (LCUV), which uses interchangeable construction implements, has been designed conceptually. Some elements of the machine have been studied in greater detail and are the focus of this report. Design of an elastic loop track system has advanced to the testing stage. A standard coupling device has been designed to insure a proper connection between the different construction tools and the LCUV. Autonomous control of the track drive motors has been simulated successfully through the use of a joystick and computer interface. A study of hydrogen-oxygen fuel cells has produced estimates of reactant and product requirements and has identified multilayer insulation needs. Research on a 100-kW heat rejection system has determined that it is necessary to transport the radiator panel on a utility trailer. Extensive logistical support for a 720-hr use cycle requires further study.

INTRODUCTION

President George Bush has made human missions to the Moon and Mars national goals. He has directed the National Aeronautics and Space Administration to develop the necessary technologies and planning that will ultimately lead to permanent bases on the Moon and Mars. A lunar base will likely evolve first because of its relative closeness to Earth. Regardless of the evolution, initial construction of these bases will rely on autonomous and teleoperated construction vehicles to reduce hazards to humans.

A rugged and reliable construction vehicle capable of performing a range of construction tasks is needed. Old Dominion University has investigated a lunar construction utility vehicle during the last two years as part of the USRA program. This vehicle is designed to perform several construction tasks by interchanging tools autonomously. The evolution of the LCUV has proceeded from a conceptual design of the overall system to a more detailed design of the coupling system for interchangeable construction implements, power generation trade-off studies, a heat rejection system design, control system strategies, and tracked locomotion design refinements. The report that follows is a current overview of the LCUV design.

AUTONOMOUS COUPLING DESIGN

One of the major purposes of the LCUV is to prepare a lunar base site for construction. To complete this task, several different operations need to be performed. However, it is advantageous to use one type of vehicle for many construction activities so that the number of machines required on the Moon is minimized. It is therefore necessary to have a vehicle (the LCUV) that is able to interchange tools for specified functions. To do so, a standard coupling device is needed for proper connection between the tools and the LCUV.

Initially it was assumed the coupling would be attached to a robotic arm mounted on top of the LCUV. However, after

consideration of the dynamic and static loadings that will occur, it was determined that resulting reaction forces and torques would be too great for robotic arms using current technology. Thus the coupling system design that has evolved anticipates mounting implements on the front of the LCUV.

The coupling design is configured as a three-point system. The receiving end of the coupling is located on the tool implement. The receiving end consists basically of a shell-like triangular box. The face of the box is open to facilitate the insertion of the locking mechanism. The locking mechanism, which is located on the front of the LCUV, attaches to an implement by rotating three levers into the tool receiving box. Each of the three levers will be driven by worm gears. Worm gears were chosen over linkages because of their ability to move the arms through greater angles. The ability to rotate the arms through an angle greater than 180° is necessary to allow for large positioning tolerances. The coupling device will be able to lift a tool vertically by raising three linkages that attach the coupler to the LCUV. The coupling will be able to rotate about the fore-and-aft axis to make the coupling and tool movement more dexterous. After the three locking levers are inserted into the box, they rotate outward and around the outside of the box, grasping pins at the outermost corners of the implement's receiving box (see Fig. 1). As the levers swing around, they pull the implement up to the coupler that is attached to the LCUV. It is then locked into position. A picture of the coupling as it would look mounted on the LCUV is shown in Fig. 2.

Provisions are made for connecting cooling fluid, data links, and electrical power lines to the implement via connections within the implement box. An interface located centrally on the coupling device mates with a female socket on the implement receiving box. A feasible design can be derived from the quick-disconnect coupling as shown in Fig. 3⁽¹⁾. With further investigation, this design may be the start of an appropriate power connection lead.

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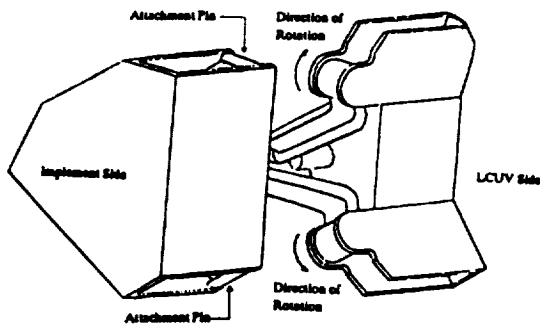


Fig. 1. Autonomous Coupling Device

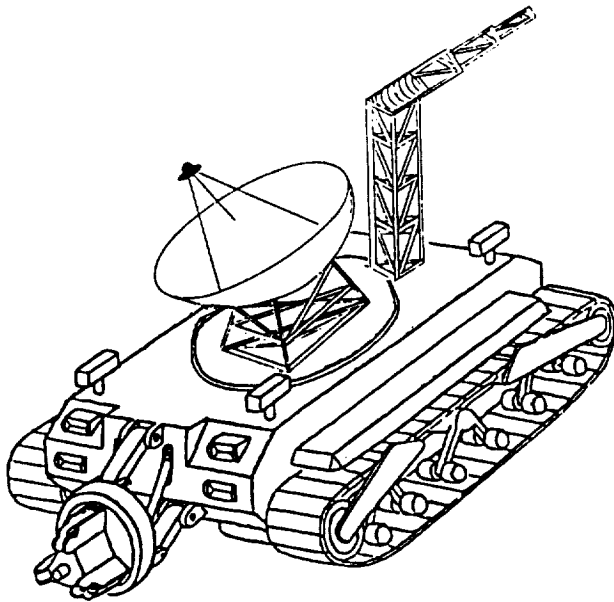


Fig. 2. LCUV with Coupling Mechanism

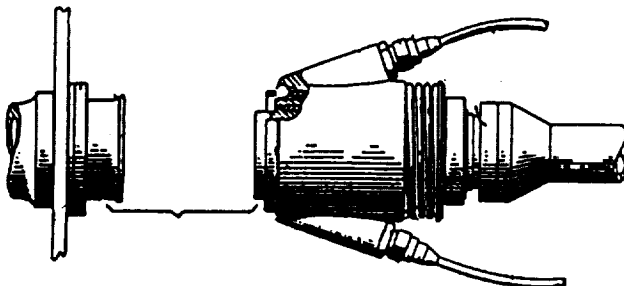


Fig. 3. Quick Disconnect Coupling

LOCOMOTION SYSTEM

The Elastic Loop Mobility System (ELMS) was originally designed by Lockheed Missiles and Space Company⁽²⁾ in the early 1970s for use on a Mars Explorer. The elastic loop system uses a continuous track that is designed to deflect when loaded. The advantages of the elastic loop system arise from its ability to deflect during dynamic loading and from its simple overall design. As the load on the track is increased, the deflection of the track results in greater contact area with the ground, thus increasing the traction of the LCUV. Probably the most important advantage of the ELMS is the built-in shock absorption provided by the track deflection. The track acts like a spring when it deflects, making the suspension system less complicated. The track design uses few moving parts, a prime objective for an unmanned vehicle in the harsh lunar environment. The configuration of the current design is shown in Fig. 4. Some design areas that needed to be addressed were loop design, telemetry box design, pivot plate construction, chassis connection, and testing procedures.

The construction of one loop, to test the mechanism of the ELMS, has been completed. Evaluation of this first loop revealed some problems that were not addressed in the initial stages of construction. Once the first loop has been debugged, a second loop can be constructed to take advantage of the modified plans. A preliminary conceptual design for the chassis connection has also been completed but work has not begun on the construction of this connection. Once construction of the connection system is completed the tracks can be attached to the LCUV chassis and testing can begin.

CONTROL SYSTEM

The research and development of an autonomous lunar construction utility vehicle requires a Locomotion Control System (LCS). The LCS is an integral part of the overall LCUV control system. The purpose of the LCS is to ensure that the drive motors are performing what the navigation control system requires, i.e., each motor rotates at the specified angular velocity.

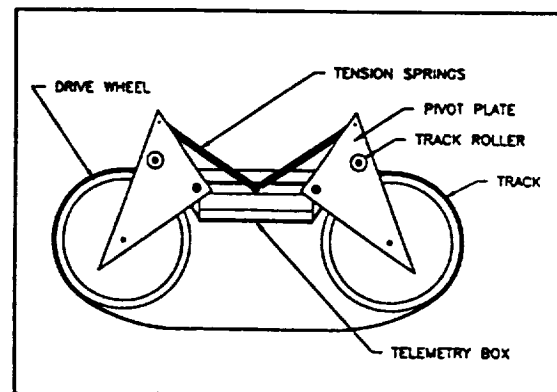


Fig. 4. Elastic Loop Track System

The LCS must operate under the lunar environmental extremes and maintain the vehicle's autonomy of operation as efficiently and reliably as possible. The task of developing this control system is explained in this section. Also, the areas of command input, control mode, output mode, and feedback measurement have been analyzed and modified. The project covers five major areas: system constraints, control system research, hardware requirements, software requirements, and problems and solutions.

The use of digital control was determined to be the best in accuracy, versatility, and cost effectiveness. A standard 286 personal computer interfaced with a Keithley 570 D/A and A/D conversion board was used as the primary control hardware. A visual representation of the control model is available in Fig. 5.

To simulate the autonomous operation of the drive motors, a joystick was used as the source of navigational information. The joystick information is scanned by the computer and the control software operates from this information in the following manner:

1. The joystick information is scanned by the computer.
2. This information is then translated into the desired angular velocity for each motor.
3. The desired angular velocity is then transferred to the Keithley board and sent to each respective motor in terms of voltage.
4. Once this voltage is applied to the motors, they rotate at a specific angular velocity, thus rotating the tachometers mounted on the drive shaft of each motor.
5. The rotation of each tachometer causes them to create a voltage.
6. This voltage is then input to the computer via the Keithley board.

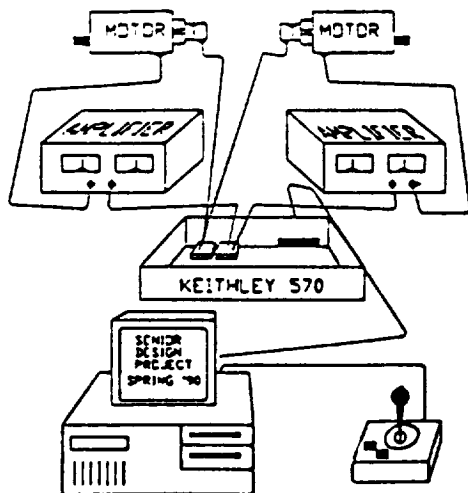


Fig. 5. Motor Controller Diagram

7. The relationship between angular velocity and voltage is linear. This relationship is described below (for a tachometer)

$$\omega = \frac{\text{Voltage}}{K_t}$$

$$K_t = 0.022$$

8. Now the computer has the values of the desired angular velocity and the actual angular velocity. The control error is then calculated. The error is the difference between these two values.

9. The control effort, U , is then determined from the error reading found by the computer. This effort is determined through the relationship

$$U = K_p \cdot \epsilon$$

$$\epsilon = (\omega_{\text{desired}} - \omega_{\text{actual}})$$

10. Step 3 is resumed by the control program until there is no error or until the computer receives new navigational information, in which event the processor would start with step 1.

POWER SUPPLY

The proposed LCUV requires a sustainable source of power for 720 hr of continuous operation. Analysis must be performed on the LCUV's requirements to determine the kind of power supply available using existing technology. When a power system for the LCUV is determined, the limitations and resources of the environment within which it operates must be taken into account. Energy from hydrogen-oxygen fuel cells was considered in the present study.

The fuel cell is a fairly simple electrochemical device. Its primary parts consist of an anode, a cathode, and an electrolyte⁽³⁾. The energy conversion occurs at the anode where the fuel (hydrogen) enters and is ionized. As this occurs, electrons are removed and travel across a load, which generates a current. The hydrogen ions then diffuse across the electrolyte. At the cathode, oxygen enters and combines with the hydrogen ions and the electrons that traverse the load. This recombination forms water, which is removed from the system. Each fuel cell can be placed in series to form a fuel cell stack which delivers a desired combined power output and voltage.

The design chosen for the reactant and product storage tanks consists of having the containers with several layers of radiation insulation mounted around their surfaces, as shown in Fig. 6. With this set-up, the outermost layer will absorb the radiation from the sun and will increase in temperature. The outer layer will radiate energy to the layer beneath it. In this process, every layer will transfer heat to the layer directly below it. This process continues until the heat reaches the surface of the tank. Therefore, by selecting the number of layers and the emissivity of the shielding material, heat transfer can be controlled. Some heat gain can be tolerated by allowing

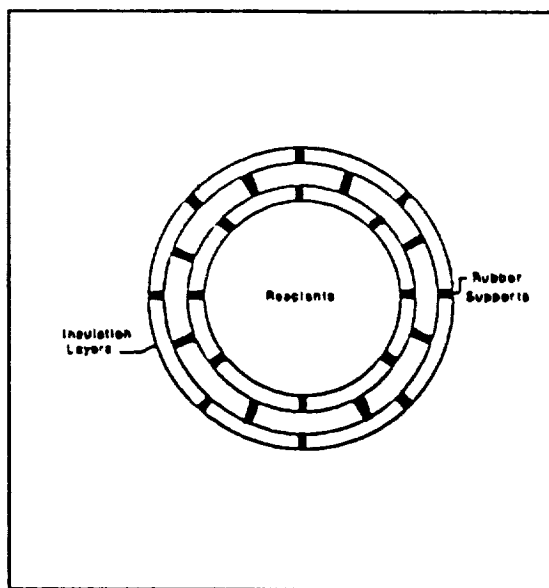


Fig. 6. Multi-Layer Insulation (Sectional View)

the liquid inside the tanks to boil. Specifically, a background or baseline rate of power generation becomes an insulation design constraint.

The insulation shield would be composed of highly polished aluminum film having low emissivity values. Low emissivity is required because resistances associated with the radiation shield become very large when emissivities are small. This would mean that lower heating rates are received by the cryogenic fluid⁽⁴⁾. Also, polished aluminum is currently available with high solar reflectance, good durability, and high flexibility.

HEAT REJECTION SYSTEM CARRIAGE

The only effective way to release heat in a lunar environment is by a radiator. To optimize the operation of the LCUV, a logistics trailer is designed to be used for housing the power supply and the heat rejection system. In order to supply coolant fluid and power to the LCUV from the carriage, a telescoping truss structure is incorporated to support the lines.

The heat rejection carriage was determined to be twice the size of the LCUV. This assumption of a 6 m by 6 m by 3-m deep vehicle was to allow for added stability.

Another major assumption was that when the radiator is fully deployed, its support platform will remain stationary in a predetermined location during a particular operation. This stationary configuration requires a collapsible truss type system to couple the radiator to the LCUV. This collapsible truss system will allow the LCUV to operate in a predetermined radius around the radiator and will also provide protection for the lines that carry the fluid and power to the radiator and its carriage.

The design of the truss selected for further consideration was a variation on a fire truck extension ladder. The ladder design possessed many of the qualities that are necessary to satisfy the design requirements that apply to the LCUV and heat-rejection unit.

For a 110-ft-long Emergency-One ladder at full extension and 0° inclination (horizontal) under an 800-lb point load at the free end, the maximum deflection was 18 in⁽⁵⁾. For application to the heat-rejection unit, distributed loads are more of a concern than point loads. The distributive loading consists of the structure's own weight, along with the weight of the fluid and power lines. Also for the LCUV, the extension unit will be supported at each end, thus deflection will occur in the center and not at the end. Due to this fact, greater extension lengths may be achieved and the extension unit can serve as an overhead crane.

HEAT REJECTION SYSTEM RADIATOR

The LCUV has a major problem with its ability to reject excess thermal energy. The solution to this problem is not an easy one; however, it is attainable through the use of a radiator. This radiator would need to be of considerable size and complexity in order to meet the heat rejection needs of the LCUV operating in the harsh lunar environment. The goal of this group has been to research the problems associated with the development of a daytime heat rejection unit that will meet the requirements of an LCUV working under the worst possible conditions on the lunar surface.

The research and design for the heat rejection unit has been carried out subject to limiting assumptions. The first assumption was that the LCUV should have the ability to perform heavy construction in the hottest lunar environment. This means that the heat rejection unit will be designed to operate at noon on the lunar equator and reject sufficient thermal energy to allow for productive LCUV operation.

The amount of thermal energy that realistically needs to be rejected is assumed to be 100 kW. This is a generous assumption and is intentionally large to prevent design shortfalls.

It is desired to operate the radiator at the lowest possible return temperature, which was determined to be approximately 340 K. This requires a radiator that is 50 ft (15 m) in length and 50 ft high. Operating the radiator much below this temperature is not feasible because it was determined that it was not possible to assume radiator surface temperatures below 340 K at lunar noon.

The radiator's large size will require it to be collapsible. It will be collapsed when the heat rejection unit is being transported along the lunar surface. If the radiator were not collapsible, considerable vibration problems would arise during transportation. The envisaged radiator can unfold in five hinged vertical panels. This will require pipe connections between the panels that can pivot to allow for this motion. The panels will be lifted from the top by one solid member that is hoisted by a cable and pulley system.

Two sides of the radiator will have vertical truss sections similar to the collapsible truss discussed for use between the LCUV and the heat rejection unit. When this truss is fully de-

played after being unloaded onto the lunar surface, the vertical trusses will extend upward to approximately 55 ft (17 m) and will remain fixed. These members will carry the radiator panel's load and will also act as guides for the radiator as it is raised and lowered.

A pulley system will be placed on top of each truss system that will be used to deploy the radiator. The cables will run from the panels up through the vertical trusses and into the carriage body where a hoist mechanism will either release or reel in the cable.

CONCLUSIONS

An autonomously operated 35-kW_e lunar construction utility vehicle (LCUV) design has been studied. The vehicle is intended for unmanned, heavy construction operations that will occur during the establishment of permanent lunar facilities and during many types of mining activities. The LCUV design study assumed continuous vehicle operation for 30 terrestrial days between refueling. Hydrogen-oxygen fuel cells were chosen as the 30-day power source, assuming a central solar-cell or nuclear power plant system is available to collect water (produced by the fuel cells) and to resupply the vehicle with liquid hydrogen and liquid oxygen.

A three-point coupling system was designed that could enable autonomous coupling of heavy construction implements without requiring precise positioning. An estimated mating tolerance of 10 cm in all directions appears feasible.

A continuous, elastic loop track design has progressed to the preliminary testing phase. Individual components have been subjected to preprototype design and testing as they have been developed. The track system continues to show desirable attributes for heavy construction operations. Interactions between the track system and control system teams produced the conclusion that only one drive motor should be used per

track, rather than the original assumption of two. A control system design has evolved that uses a joy stick to generate digital signals that can simulate the command stream that will occur during lunar operations. Successful control of two motors has been demonstrated.

The heat rejection system was designed under a worst-case scenario. It was determined that the LCUV could generate 100 kW of heat on the Moon's equator. A radiator that could reject this heat would have to be approximately 50 ft long by 50 ft high. A separate logistics trailer has been conceptualized to house the heat rejection unit because the radiator's large size would restrict the LCUV's capabilities. A truss type of structure was incorporated in the design to support the power and coolant lines between the trailer and the LCUV.

More research is needed in the power and heat rejection systems. The large size of the fuel tanks and radiator require an independent, self-contained unit to support the LCUV. One way to reduce the size would be to use a solar power system, operated only during lunar daytime, instead of continuous operation with fuel cells. This would reduce the overall weight of the vehicle by eliminating the large fuel tanks as well as remove the central power station requirement. However, a solar panel of nearly the same dimensions as the radiator would be needed. This alternate design needs further investigation.

REFERENCES

1. Paine, Thomas, Allan McDougal, and Douglas Davis. "Quick-Disconnect Coupling," US Patent No. 3,656,781, Apr. 18, 1972.
2. Trautwein, W. "Design, Fabrication, and Delivery of an Improved Single Elastic Loop Mobility System (ELMS)," Lockheed Missiles and Space Co., NASA Contractor Rpt, NASA-CR-123841, July 1972.
3. Parrish, M. A. "Fuel Cells—A Survey," *Materials in Engineering*, Vol. 2, No. 2, pp. 68-72, Dec. 1980.
4. Incropera, Frank P., and David P. Dewitt. *Fundamentals of Heat and Mass Transfer*, John Wiley and Sons, New York, 1985.
5. Aiken, Jeff, Project Engineer, Emergency-One Inc., Ocala, Fla., Personal Interview, March 30, 1990.

